Moduli and a Cosmic Axion Background

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Experimental Search for Quantum Gravity
Frankfurt IAS
19th September 2016

Talk Structure

1. Quantum Gravity and Moduli
2. The Cosmological Moduli Problem
3. A 0.1 - 1 keV Cosmic Axion Background
4. Observing a Cosmic Axion Background and the Cluster Soft Excess

Thanks to my collaborators

1208.3562 Michele Cicoli, JC, Fernando Quevedo
'Dark Radiation in LARGE Volume Models'

1304.1804 JC, David Marsh
'The Cosmophenomenology of Axionic Dark Radiation'

1305.3603 JC, David Marsh
'Searching for a 0.1-1 keV Cosmic Axion Background'

1312.3947 Stephen Angus, JC, David Marsh, Andrew Powell, Lukas Witkowski
'Soft X-Ray Excess in the Coma Cluster from a Cosmic Axion Background'

1406.5188 David Kraljic, Markus Rummel, JC
'ALP Conversion and the Soft X-Ray Excess in the Outskirts of the Coma Cluster'

I
QUANTUM GRAVITY AND MODULI

Quantum Gravity

The experimental study of quantum gravity is a big task.

I will restrict to one narrower aspect of it: how to establish the existence of

- Quantised particle states
- That interact with gravitational strength couplings
- Through observational/experimental means

In particular, I will focus on massive, gravitationally coupled scalars - called moduli in string theory, but not restricted only to there.

Moduli in String Theory

How to turn string compactifications into observational predictions?

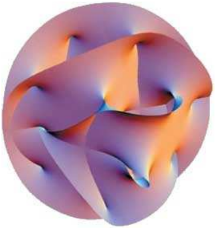
A landscape of ways to approach the Standard Model:

- Weakly coupled heterotic string
- Free fermionic models
- Rational CFT models (Gepner models)
- IIA intersecting D6 branes
- Branes at singularities
- M-theory on singular G2 manifolds
- IIB magnetised branes with fluxes
- F-theory
- ...

Moduli

Given the landscape, how to turn string compactifications into observational predictions?

Focus on the most generic aspect of compactification: moduli.



Dimensional reduction of 10d graviton gives scalars (moduli) in 4 dimensions.

Much of the physics of moduli is universal across compactifications.

Moduli

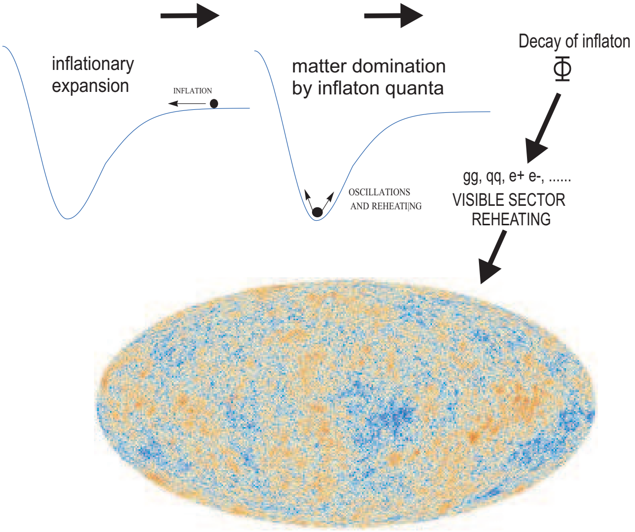
Particles that interact with gravitational strength

- Are hard to make
- Interact more weakly than Standard Model particles
- For the same mass, live longer than Standard Model particles.

Cosmology is a good place to look for particles that can survive a long time without decaying

II
THE COSMOLOGICAL MODULI PROBLEM

The Standard Cosmology:



The Cosmological Moduli Problem

Polonyi 81, Coughlan Ross 83, Banks Kaplan Nelson 93, de Carlos Casas Quevedo Roulet 93

Hot Big Bang starts when universe becomes radiation dominated.

This occurs 'when inflaton decays'. However:

- Non-relativistic matter redshifts as $\rho_\Phi \sim a(t)^{-3}$
- Radiation energy density redshifts as $\rho_\gamma \sim a(t)^{-4}$
- Therefore as $a(t) \to \infty$, $\frac{\rho_\gamma}{\rho_\Phi} \to 0$

Long-lived matter comes to dominate almost independent of the initial conditions.

Reheating is dominated by the LAST scalar to decay NOT the first.

The Cosmological Moduli Problem

Like axions, during inflation moduli are generally misaligned from their final minimum.

Misalignment occurs as inflationary potential contributes to the moduli (S, T) potential:

$$V_{inf} = V_{inf}(S, T, \dots)$$

After inflation, moduli oscillate as non-relativistic matter ($\rho \sim a^{-3}$) before decaying.

As moduli have gravitational-strength couplings, their interactions are suppressed by powers of M_P.

Moduli live a long time and come to dominate the energy density of the universe.

The Cosmological Moduli Problem

Lifetime of moduli is determined by M_P-suppressed decay rate:

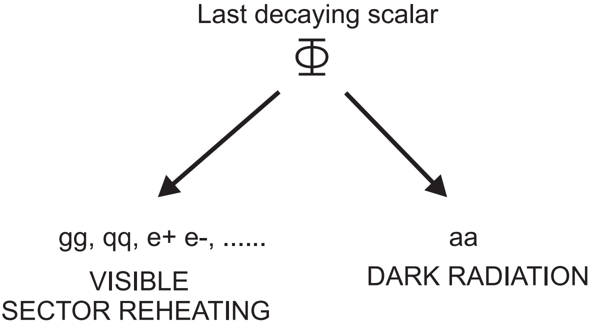
$$\begin{aligned} \Gamma &\sim \frac{1}{8\pi}\frac{m_\Phi^3}{M_P^2} \\ \tau &= \Gamma^{-1} \sim 8\pi \frac{M_P^2}{m_\Phi^3} = \left(\frac{100\text{TeV}}{m_\Phi}\right)^3 0.1\text{s} \\ T_{decay} &\sim \left(\frac{m_\Phi}{100\text{TeV}}\right)^{3/2} 3\text{ MeV} \end{aligned}$$

Hot Big Bang does not start until moduli decay - potential problem!

Side consequence: generic expectation of string compactifications is that the universe passes through a modulus-dominated epoch, and reheating comes from the decays of these moduli.

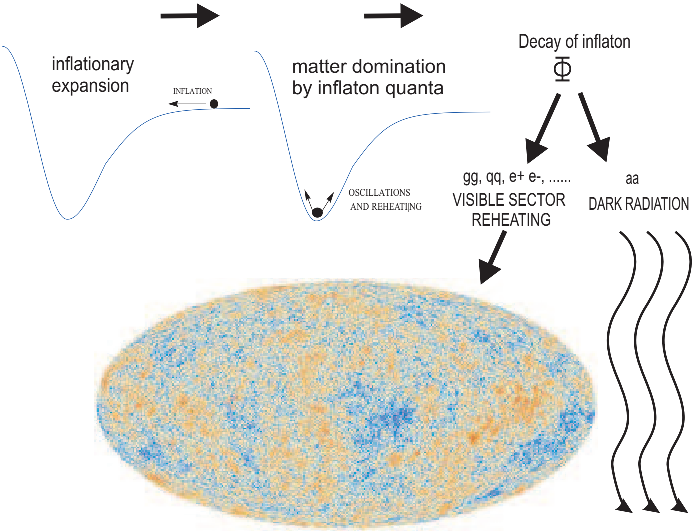
The Cosmological Moduli Opportunity

We expect reheating to be driven by the late-time decays of massive Planck-coupled particles.



Hidden sector decays of moduli (e.g. to axions a) give rise to dark radiation.

The Cosmological Moduli Opportunity



Dark Radiation: Physics

Both the CMB and primordial BBN abundances are sensitive to additional dark radiation in the early universe (which changes the expansion rate).

In the CMB, ΔN_{eff} modifies the damping tail of the CMB and is probed by the ratio between the damping scale and the sound horizon.

At BBN times, extra radiation modifies the expansion rate at a given temperature.

This affects the primordial Helium and Deuterium abundances: $(D/H)_p$ (where N_{eff} is degenerate with $\Omega_b h^2$) and Y_p.

Still room for dark radiation up to $\Delta N_{eff} \sim 0.5$ (cf CMB/local H_0 measurement contreversy).

The Cosmological Moduli Opportunity

As gravitationally coupled particles, moduli generally couple to everything with M_P^{-1} couplings and there is no reason to expect vanishing couplings to hidden sectors.

$$\begin{aligned} \text{Visible sector} \quad &: \quad \frac{\Phi}{4M_P} F^{color}_{\mu\nu} F^{color,\mu\nu}, \; \frac{\partial_\mu \partial^\mu \Phi}{M_P} H_u H_d, \ldots \\ \text{Hidden sector} \quad &: \quad \frac{\Phi}{2M_P} \partial_\mu a \partial^\mu a, \; \frac{\Phi}{4M_P} F^{hidden}_{\mu\nu} F^{hidden,\mu\nu} \ldots \end{aligned}$$

This is supported by explicit studies of string effective field theories

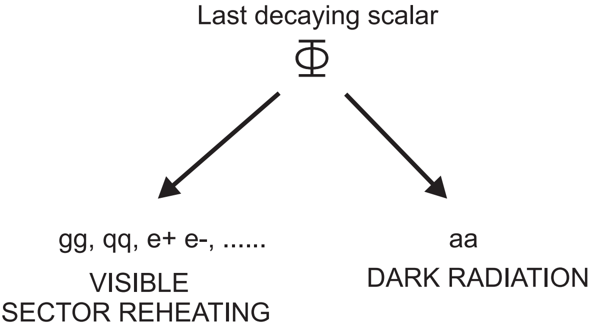
In particular, axionic decay modes naturally arise with $\text{BR}(\Phi \to aa) \sim 0.01 \to 1$.

1208.3562 Cicoli JC Quevedo, 1208.3563 Higaki Takahashi, 1304.7987 Higaki Nakayama Takahashi

III
A COSMIC AXION BACKGROUND

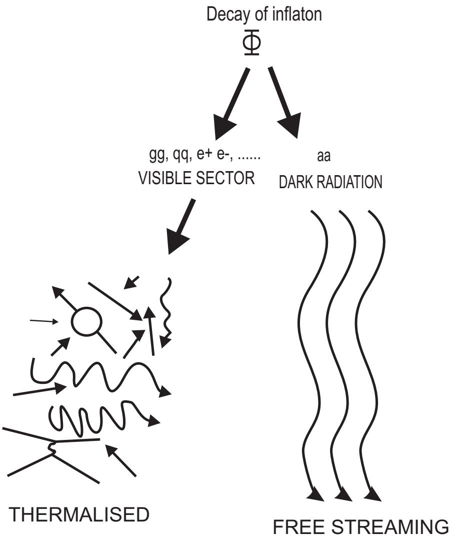
A Cosmic Axion Background

An expectation in string theory that we should expect reheating to be driven by the late-time decays of massive Planck-coupled particles.



Dark radiation arises from hidden sector decays of moduli

A Cosmic Axion Background



A Cosmic Axion Background

Typical moduli couplings $\frac{\Phi}{4M_P}F_{\mu\nu}F^{\mu\nu}$ or $\frac{\Phi}{M_P}\partial_\mu a \partial^\mu a$ give

$$H_{decay} \sim \Gamma \sim \frac{1}{8\pi}\frac{m_\Phi^3}{M_P^2}$$

$$\begin{aligned} T_{reheat} & \sim \left(3H_{decay}^2 M_P^2\right)^{1/4} \sim \frac{m_\phi^{3/2}}{M_P^{1/2}} & \sim 0.6\text{GeV}\left(\frac{m_\phi}{10^6\,\text{GeV}}\right)^{3/2} \\ E_{axion} & = \left(\frac{m_\Phi}{2}\right) = & 5\times 10^5\,\text{GeV}\left(\frac{m_\Phi}{10^6\,\text{GeV}}\right) \end{aligned}$$

Visible sector thermalises: however axions propagate freely as universe is transparent to them.

A Cosmic Axion Background

$$\Phi \to gg, \ldots : \quad \text{Decays thermalise} \quad T_\gamma \sim T_{reheat} \sim \frac{m_\Phi^{3/2}}{M_P^{\frac{1}{2}}}$$

$$\Phi \to aa : \quad \text{Axions never thermalise} \quad E_a = \frac{m_\Phi}{2}$$

Thermal bath cools into the CMB while axions never thermalise and freestream to the present day:

Ratio of axion energy to photon temperature is

$$\frac{E_a}{T_\gamma} \sim \left(\frac{M_P}{m_\Phi}\right)^{\frac{1}{2}} \sim 10^6 \left(\frac{10^6 \text{GeV}}{m_\Phi}\right)^{\frac{1}{2}}$$

Retained through cosmic history!

A Cosmic Axion Background

Ratio of axion energy to photon temperature is

$$\frac{E_a}{T_\gamma} \sim \left(\frac{M_P}{m_\Phi}\right)^{\frac{1}{2}} \sim 10^6 \left(\frac{10^6\text{GeV}}{m_\Phi}\right)^{\frac{1}{2}}$$

No absolute prediction for moduli masses (need $m_\Phi \gtrsim 10^5\mathrm{GeV}$ to ensure decays before BBN)

A scale $m \sim 10^6$GeV often arises in models based on SUSY approaches to the weak hierarchy problem.

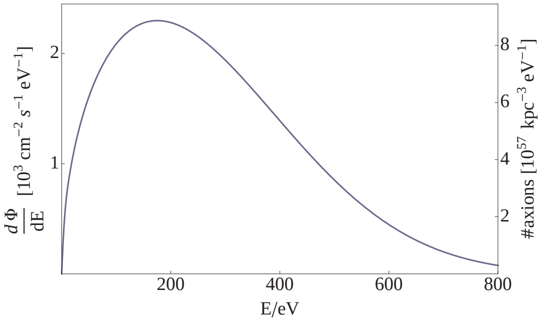
- KKLT hep-th/0503216 Choi et al
- Sequestered LVS 0906.3297 Blumenhagen et al
- 'G2 MSSM' 0804.0863 Acharya et al

A Cosmic Axion Background

Axions originate at $z \sim 10^{12} (t \sim 10^{-6}$ s) and freestream to today.

PREDICTION: Cosmic Axion Background

Energy: $E \sim 0.1 \div 1\text{keV}$ Flux: $\sim \left(\frac{\Delta N_{eff}}{0.5}\right) 10^6 \text{cm}^{-2}\text{s}^{-1}$.



A Cosmic Axion Background

The current energy of such axionic dark radiation is

$$E_a \sim 200\text{eV} \left(\frac{10^6 \text{ GeV}}{m_\Phi} \right)^{\frac{1}{2}}$$

The expectation that there is a dark analogue of the CMB at $E \gg T_{CMB}$ comes from very simple and general properties of moduli.

It is not tied to any precise model for moduli stabilisation, or approach to realising the Standard Model.

It just requires the existence of massive particles only interacting gravitationally.

For $10^5\text{GeV} \lesssim m_\Phi \lesssim 10^8\text{GeV}$ CAB lies today in extreme ultraviolet /soft X-ray wavebands.

IV
OBSERVING A COSMIC AXION BACKGROUND

Seeing Axions

How to see a CAB with $E_a \sim 0.1 - 1\mathrm{keV}$?

Axion-photon conversions come from axion coupling to electromagnetism:

$$\mathcal{L}_{a-\gamma} = -\frac{1}{4}F_{\mu\nu}F^{\mu\nu} - \frac{1}{4M}aF_{\mu\nu}\tilde{F}^{\mu\nu} + \frac{1}{2}\partial_\mu a \partial^\mu a - \frac{1}{2}m_a^2 a^2.$$

For general axion-like particles $M \equiv g_{a\gamma\gamma}^{-1}$ and m_a are unspecified.

We take $m_a = 0$ (in practice all results hold for $\lesssim 10^{-12}$eV) and keep M free.

Direct bounds (axion production in supernovae, no large spectral modulations from NGC1275) are $M \gtrsim 10^{11}$GeV.

Seeing Axions

Axion-to-photon conversion probability for axion energy E_a in transverse magnetic field $B_\perp$ of domain size L is:

$$P(a \to \gamma) = \sin^2(2\theta)\sin^2\left(\frac{\Delta}{\cos 2\theta}\right)$$

where

$$\theta \approx 2.8\cdot 10^{-5} \times \left(\frac{10^{-3}\mathrm{cm}^{-3}}{n_e}\right)\left(\frac{B_\perp}{1\ \mu\mathrm{G}}\right)\left(\frac{E_a}{200\ \mathrm{eV}}\right)\left(\frac{10^{14}\ \mathrm{GeV}}{M}\right),$$

$$\Delta = 0.27 \times \left(\frac{n_e}{10^{-3}\mathrm{cm}^{-3}}\right)\left(\frac{200\ \mathrm{eV}}{E_a}\right)\left(\frac{L}{1\ \mathrm{kpc}}\right).$$

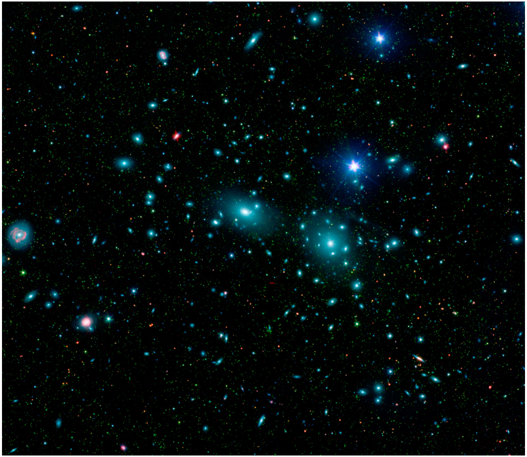
Seeing Axions

Axions convert to photons in coherent magnetic field domain: want large magnetic fields supported over large volumes.

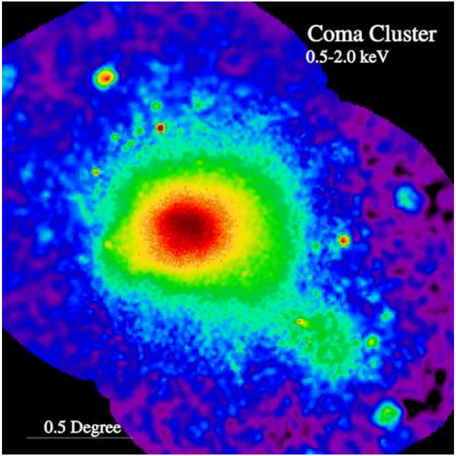
Best locations are galaxy clusters:

- The largest virialised structures in the universe
- Typical size 1 Mpc, typical mass $10^{14} \div 10^{15} M_{sun}$.
- Large magnetic fields $B \sim 1 \div 10\mu$G coherent over $L \sim 1 \div 10$ kpc.
- Hot intracluster gas, $T_{gas} \sim 2 \div 10$keV.
- By mass 1 per cent galaxies, 10 per cent gas, 90 per cent dark matter.
- Sit at the 'large magnetic fields over large volumes' frontier of particle physics.

The Coma Cluster in IR/Visible



The Coma Cluster in X-rays



The Cluster Soft Excess

In fact there exists a long-standing (since 1996) EUV/soft x-ray excess from galaxy clusters (Lieu 1996, review Durret 2008). E.g Coma has

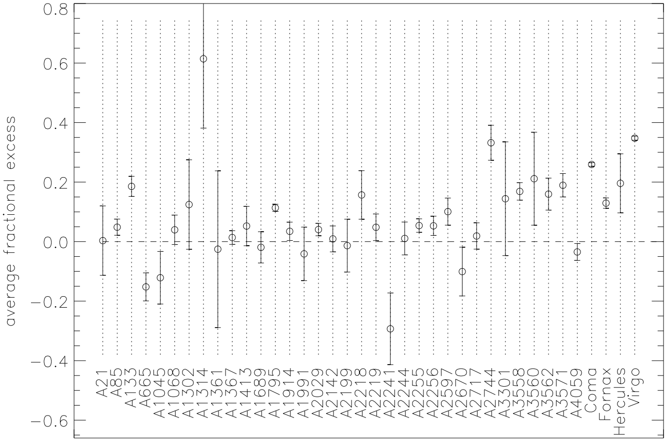
$$\mathcal{L}_{excess} \sim 10^{43} \text{erg s}^{-1}$$

Observed by different satellites - principally EUVE and soft bands of ROSAT.

Has been studied for a large number (~ 40) of clusters, present in ~ 15.

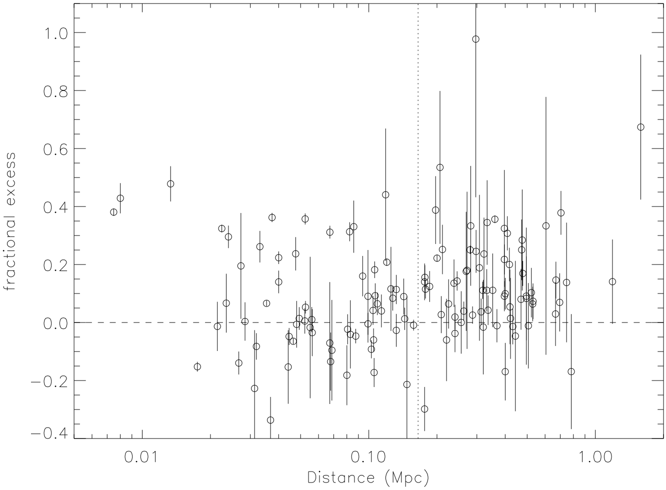
Difficulties with astrophysical explanations - see backup slides.

The Cluster Soft Excess



from Bonamente et al 2002, fractional soft excess in ROSAT 0.14 - 0.28 keV R2 band

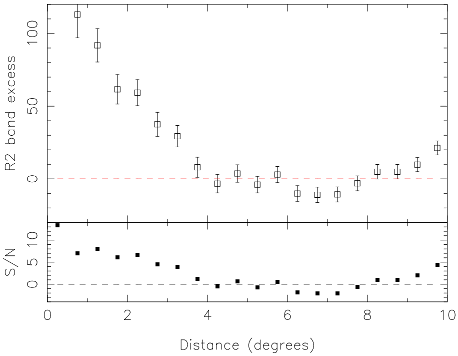
The Cluster Soft Excess



from Bonamente et al 2002, fractional soft excess with radius

The Cluster Soft Excess: Coma

Soft excess extends well beyond hot gas and cluster virial radius:



from 0903.3067 Bonamente et al, ROSAT R2 band (0.14-0.28keV) observations of Coma

The Cluster Soft Excess and a CAB

Proposal: cluster soft excess generated by $a \to \gamma$ conversion in cluster magnetic field.

Basic predictions:

- Magnitude and morphology of soft excess fully determined by cluster magnetic field and electron density
- Spatial extent of excess conterminous with magnetic field
- No thermal emission lines (e.g. O_{VII}) associated to excess
- Energy of excess is constant across clusters, varying with redshift as $E_a \sim (1 + z)$.

Test by propagating axions through simulated cluster magnetic fields

Axion Propagation through Center of Coma Cluster

Magnetic field model is best fit to Faraday rotation (Bonafede et al 1002.0594):

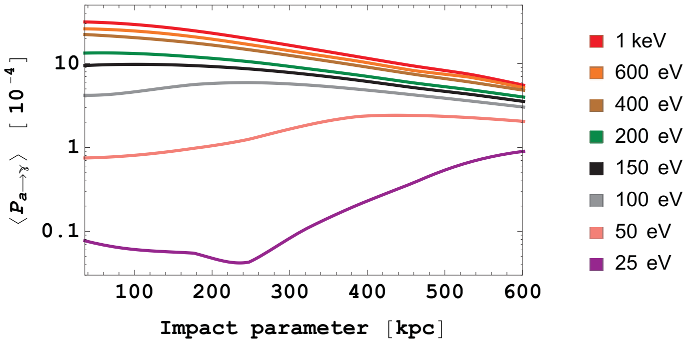
- Magnetic field has Kolmogorov spectrum, $|B(k)| \sim k^{-11/3}$, generated between $k_{max} = \frac{2\pi}{2\text{kpc}}$ and $k_{min} = \frac{2\pi}{34\text{kpc}}$.
- Spatial magnetic field has Gaussian statistics.
- Central magnetic field $\langle B \rangle_{r<291kpc} = 4.7\mu\text{G}$
- Equipartition radial scaling of B, $B(r) \sim n_e(r)^{1/2}$
- Electron density taken from β-model with $\beta = 0.75$,

$$n_e(r) = 3.44 \times 10^{-3} \left(1 + \left(\frac{r}{291\text{kpc}}\right)^2\right)^{-\frac{3\beta}{2}} \text{cm}^{-3}$$

- Numerical 2000^3 magnetic field with 0.5kpc resolution.

Numerical propagation of axions with $E = 25\text{eV} \div 25000\text{eV}$ and determination of $P(a \to \gamma)$.

Axion Propagation through Centre of Coma

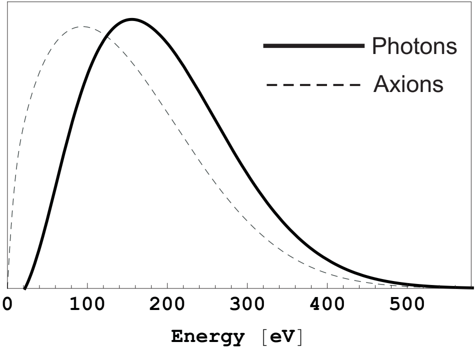


$a \to \gamma$ conversion probabilities for different axion energies as a function of radius from the centre of Coma

Note the high suppression for $E_a < 100\text{eV}$

Angus JC Marsh Powell Witkowski 1312.3947

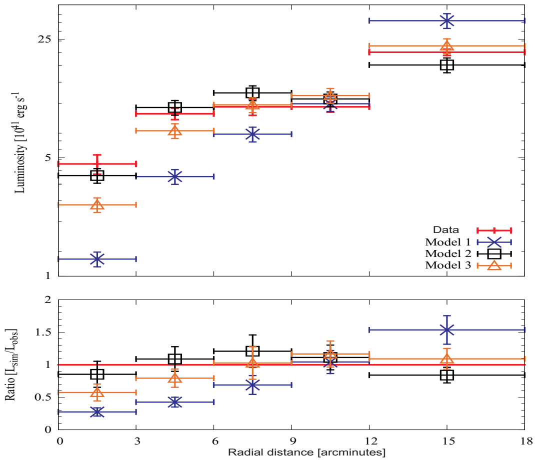
Axion Propagation through Centre of Coma



Comparison of original axion spectrum and spectrum of converted photons

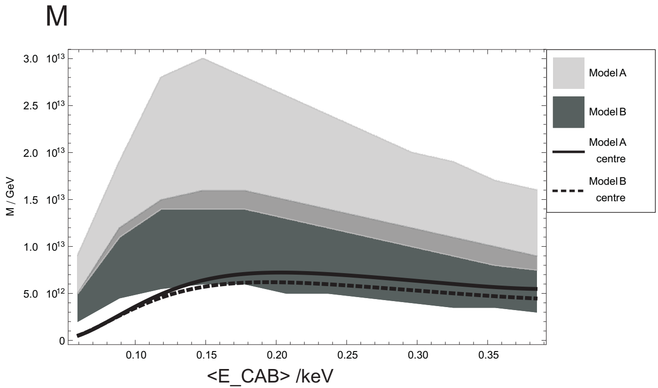
Photon spectrum falls off rapidly at both low and high energies

Axion Propagation through Centre of Coma



Morphology fits reasonably well for $M \sim 7 \times 10^{12}\mathrm{GeV}$

Axion Propagation through Outskirts of Coma



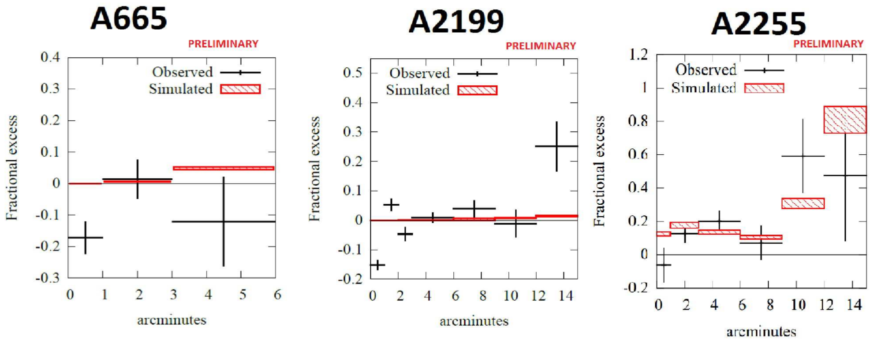
Fit to the outskirts gives a compatible value of $M \sim 10^{13}\mathrm{GeV}$.

Kraljic, Rummel, JC 1406.5188

Axion Propagation through Other Clusters

(Plots assume the Coma best fit value of $M \sim 7 \times 10^{12}$GeV)

Powell



Conclusions

- What are observational traces of quantised, gravitationally coupled, massive scalar particles (moduli)?
- One trace could be the existence of a Cosmic Axion Background with energies $E_a \gg T_{CMB}$
- CAB arises from decays of moduli to axions at the time of reheating, and contributes to dark radiation.
- CAB energy today is naturally in $0.1 - 1$ keV range
- Axions can convert into photons in astrophysical magnetic fields, and CAB may be responsible for long-standing soft X-ray excess from galaxy clusters

BACKUP SLIDES

Cluster Soft Excess: Astrophysical Explanations

Two main proposals for astrophysical explanations:

1. A warm thermal gas with $T \sim 0.2\text{keV}$.

   Interpret soft excess as thermal bremmstrahlung emission from this warm gas.

2. A large non-thermal relativistic electron population with $E \sim 200 - 300$ MeV.

   Interpret soft excess as inverse Compton scattering of electrons on CMB.

Both have problems (in back-up slides).

Astrophysics: $T \sim 0.2$keV warm gas

The original proposal. However:

1. Such a gas is pressure unstable against the hot ICM gas.

   It rapidly cools away on a timescale much shorter than cluster timescales.

2. A thermal $T \sim 0.2$keV gas would also have thermal emission lines - particularly O_{VII} at 560 eV.

   No such lines have been observed - some early claimed detections have gone away.

Astrophysics: non-thermal $E \sim 150$ MeV electrons

A more promising propsal: a large population of non-thermal electrons scattering off the CMB. However:

1. If this population continues to $E \sim 2$GeV, its synchrotron radio emission is above level of Coma radio halo.

   This necessitates a sharp spectral cutoff between ~ 200MeV and ~ 2GeV.

2. This population necessarily produces gamma rays through non-thermal bremmstrahlung.

   It was predicted that these gamma rays would be easily observable by Fermi (Atoyan + Volk 2000)

   But - Fermi does not see any clusters:

$$\mathcal{F}^{Coma}_{>100 \text{ MeV}} < 1.1 \times 10^{-9} \text{ph cm}^{-2} \text{ s}^{-1}$$

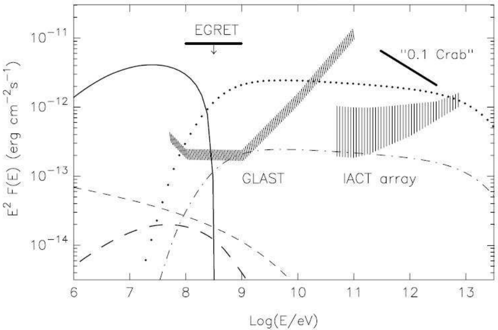
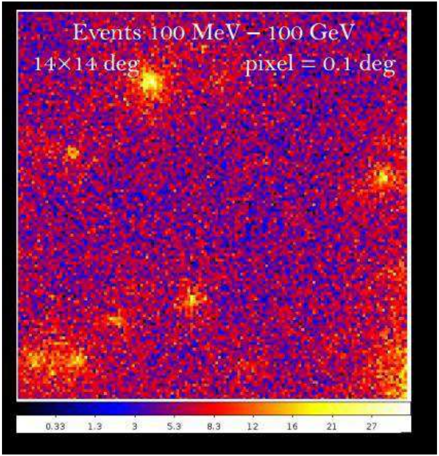


FIG. 6.—Expected γ-ray fluxes expected from the Coma Cluster. The

from Atoyan + Volk, 2000

Coma in Gamma Rays



(Ando + Zandanel, 1312.1493)